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ELECTROMAGNETIC GAUGE OF TUBE INNER RADIUS COMPENSATED FOR MATERIAL PROPERTIES AND COIL RADIAL OFFSET

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Abstract – Low-frequency electromagnetic measurement of inner radius of metal tubes is indispensable in their production and condition assessment. Two challenges in such a measurement are corrections for variations in electromagnetic properties of a tube and coil radial offset. The authors investigate adaptation of the single-coil method for measurement of inner radius to a small scale embedded system based on a DSP microcontroller. The electromagnetic gauge can be used for both magnetic and nonmagnetic tubes and its performances are comparable to the laboratory implementation of the method based on a precision RLC meter.

Keywords: impedance measurement, diameter gauge, embedded system

1. INTRODUCTION

Low-frequency electromagnetic measurement of inner radius of metal tubes is indispensable in the production and assessment of their condition and remaining useful life especially in harsh industrial environments [1–3]. Methods for measurement of inner radius are based on measurements of a single coil impedance or a voltage induced in a receiver coil [4–5].

Electromagnetic properties of the tube (relative magnetic permeability and electrical conductivity) strongly affect the coil impedance or induced voltage, thus imposing the need for correction of the measurement [5]. This is traditionally achieved using simplified models or calibration of an instrument using tubes with known radii and the same electromagnetic properties as the tube under inspection [2–5]. However, the electromagnetic properties of metal tubes are usually specified with large tolerances and they are subject to the temperature changes. Conductivity and especially permeability can vary significantly between tubes made of the same materials and even along the tube, depending on the manufacturing process, impurities and previous material's magnetic history [6].

The second problem is centering of the coils inside the tube during the measurement. Slight misalignment of the axes of the coil and tube (i.e. coil radial offset) introduces errors in inner radius measurement [7, 8]. This can be avoided using mechanical centralizers, but they are cumbersome and sometimes impossible to deploy. Hence, there is a need for an electromagnetic gauge of tube inner radius that would not require the calibration with respect to the electromagnetic properties and coil centering.

In our previous work, we presented a model-based method for measurement of the tube inner radius independently from the tube electromagnetic properties [8–10]. Laboratory measurement set-up was based on the precision RLC meter and we used several coils in the frequency range 1 kHz–1 MHz [10]. The inversion procedure for determination of inner radius from measured coil impedance relied on optimization algorithms that required computational power of an ordinary personal computer [10].

There remained an open question on how to adapt the method to a small scale embedded system suitable for field measurements. The most important requirements for such a system are acceptable accuracy and resolution of the impedance measurement with respect to the sensitivity of the method, whereas the most limiting factor is available computational power that dictates the simplicity of the inversion procedure [11].

In this paper, we investigate required modifications to the measurement method and practical aspects of its implementation in an embedded system. The paper is organized as follows. In Section 2 we briefly describe the underlying analytical impedance model, propose an inversion procedure based on a lookup table and describe correction for the coil radial offset. Design of the proposed embedded system is sketched in Section 3. We compare performances of the system with the laboratory set-up based on the precision RLC meter and personal computer in Section 4. Section 5 contains conclusions.

2. MEASUREMENT METHOD

2.1. Coil impedance model

The total impedance of a single-layer cylindrical coil axially centered inside a metal tube is sum of the impedance of the coil in air (i.e. out of tube) Z_{air} and a contribution Z_T of the tube [9]:

$$Z = Z_{air} + Z_T \,. \tag{1}$$

At frequencies for which the tube wall thickness can be considered infinite, the impedance Z_T is [10]:

$$Z_T = j\omega \int_0^{\infty} C\left(\alpha, L, r_0, S, N_t\right) T\left(\alpha, PCR, r, \omega\right) d\alpha \,, \qquad (2)$$

where α is an integration variable, C depends on coil dimensions (length L, radius r_0, cross-section S, number of turns N_t) and T is "tube contribution" since it is the only function that depends on the tube properties (permeability-to-conductivity ratio $PCR=\mu_r/\sigma$ and inner radius r). Derivation of (2), sensitivity analysis and discussion on choice of the measurement frequency have been given in details elsewhere [10].

2.2. Inversion procedure

The simplest approach to the inversion procedure, i.e. determining the inner radius from the measured impedance, is to use a lookup table, although more advanced algorithms can be implemented depending on available processing power [10]. Minimal radius r_{min} that can be measured is determined by the radius of the coil and maximal radius r_{max} is limited by the resolution and accuracy of the impedance measurement. Thus, it is possible to form a two-dimensional lookup table $Z_T(r_i, PCR_j)$ for $i=1,...,N$ and $j=1,...,M$ with the intervals $[r_{min}, r_{max}]$ and $[PCR_{min}, PCR_{max}]$ divided into N and M discrete values, respectively. Since one usually has a general idea about the type of the tube's material (e.g. steel, copper, aluminum), the size of the table can be reduced further by choosing the corresponding interval $[PCR_{min}, PCR_{max}]$.

The tube radius is determined from the lookup table by finding the pair (r_i,PCR_j) that minimizes the module of the difference between measured $Z_{T,meas}$ and $Z_T(r_i, PCR_j)$. Thus, the measured tube properties are:

$$\left(r, PCR\right) = \min_{(i,j)} \left| Z_{T,meas} - Z_T\left(r_i, PCR_j\right) \right| \,, \qquad (3)$$

where r is the tube inner radius corrected for tube's conductivity and permeability. The step between two consecutive values r_i and r_{i+1} is determined from the sensitivity of the coil impedance to change of the tube radius, resolution of the impedance measurement and available memory space.

2.3. Effect of coil radial offset

The resistance of a coil placed inside a conductive tube is minimal if the coil is axially centered [10]. The coil usually hangs from the cables and swings while lowered down into the tube. This can be used to minimize the effect of coil radial offset by taking several impedance measurements at one position and finding the minimal value of the coil resistance and its corresponding inductance. One requires 10–50 samples of the impedance (total measurement time about 1–5 s) at one position to obtain a good approximation of the impedance of the perfectly centered coil.

There is also a possibility of including the coil radial offset into the coil impedance model. This, however, significantly complicates the model equations and the inversion procedure [8].

3. SYSTEM DESIGN

The electromagnetic inner radius gauge is designed around an analog module for driving a measurement coil at a single excitation frequency and an embedded system dedicated to the digital synthesis of the excitation signal, acquisition and real-time processing of measured data and serial communication. The system can accommodate coils of different size and impedance in order to achieve maximal fill factor and measurement range of tube radius.

3.1. Analog module

Since the relative permeability of the tube material depends on the applied magnetic field strength, the measurement should be made using the constant magnitude of the magnetic field. Thus, we applied the constant current excitation using a voltage-to-current converter, Fig. 1. Differential voltage $u_D=u_{D+}-u_{D-}$ at the output of the direct digital synthesis (DDS) integrated circuit AD9834 (*Analog Devices Inc.*) is fed to the input of the instrumentation amplifier, Fig 2. The negative feedback is achieved connecting the voltage drop of the load $Z+R_{ref}$ to the reference terminal of the instrumentation amplifier via the voltage follower. The output of the instrumentation amplifier is:

$$u_O = A_D u_D + u_{ref} \,, \qquad (4)$$

and the load current i_L is given with:

$$i_L = \frac{A_D u_D}{R_S} \,, \qquad (5)$$

where A_D is differential gain of the instrumentation amplifier. According to (5), the load current does not depend on the load Z and can be adjusted using R_S. We implemented the converter using AD620 (*Analog Devices Inc.*) as the instrumentation amplifier and OP97 (*Analog Devices Inc.*) as the voltage follower. Two signals u_V and u_C that correspond to the voltage and current of the series of the coil and reference resistor are connected to the digital module via dual buffer amplifier OP270 (*Analog Devices Inc.*). Signal-to-noise ratio for u_V and u_C was better than 75 dB for frequency bandwidth of 50 kHz, i_L=2 mA and all tested loads.

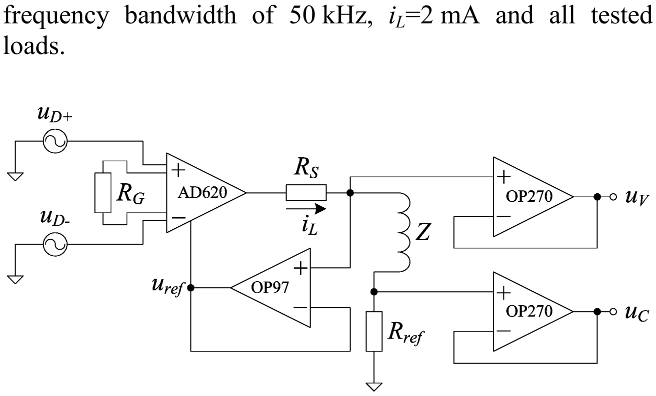

Fig. 1. Voltage-to-current converter and the measurement coil as a load *Z*.

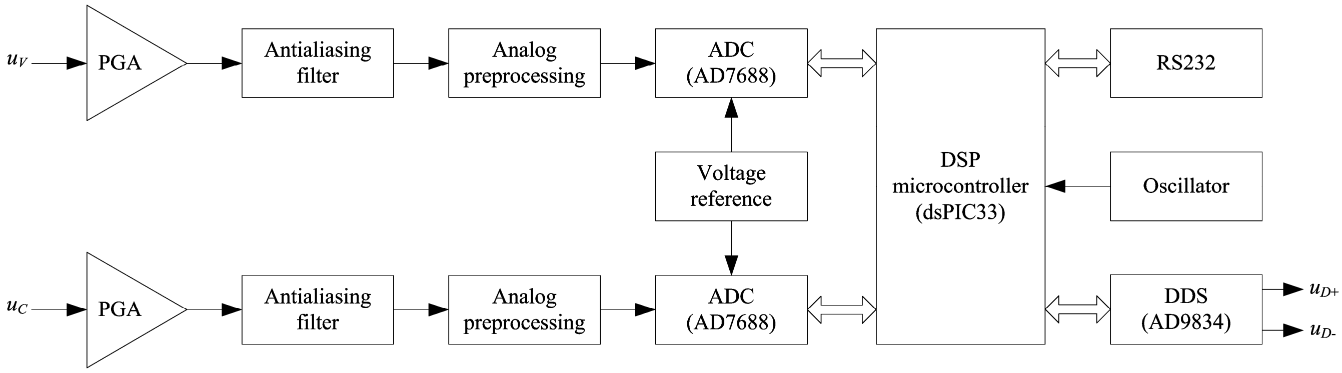

Fig. 2. Principle block-diagram of the digital module.

3.2. Digital module

The digital module is an embedded system dedicated to two-channel 16-bit digital acquisition and signal processing required for measurement of the tube inner radius, Figs. 2 and 3. The module is built around a microcontroller from dsPIC33 (*Microchip Technology Inc.*) family, chosen because of its computational capabilities of a DSP and simplicity and control features of a microcontroller. The controller has 256 kB of ROM, 32 kB of RAM and is capable of executing 40 MIPS at the clock frequency of 80 MHz.

Two voltage signals u_V and u_C from the analog module in Fig. 1 are fed to two independent analog-to-digital converters AD7688 (*Analog Devices Inc.*) via programmable gain amplifiers, antialiasing filters and single-ended-to-differential drivers (analog preprocessing in Fig. 2). AD7688 is a differential 16-bit, charge redistribution, successive approximation analog-to-digital converter with 500 kHz sampling rate. The converters are connected to the controller using serial peripheral interface (SPI). The voltage and current signals are sampled synchronously in order to keep their phase relation.

Digitalized voltage and current signals are fed to digital lock-in amplifier and low-pass filter implemented in the microcontroller to obtain their respective in-phase and quadrature components from which corresponding magnitude and phase can be calculated. In order to minimize the computational burden, the sampling frequency is exactly four times higher than the excitation frequency, what reduces the sine and cosine terms in the lock-in implementation to ±1 or 0 [12]. The final result (inner radius determined from the lookup table) is communicated to a display using RS232 interface.

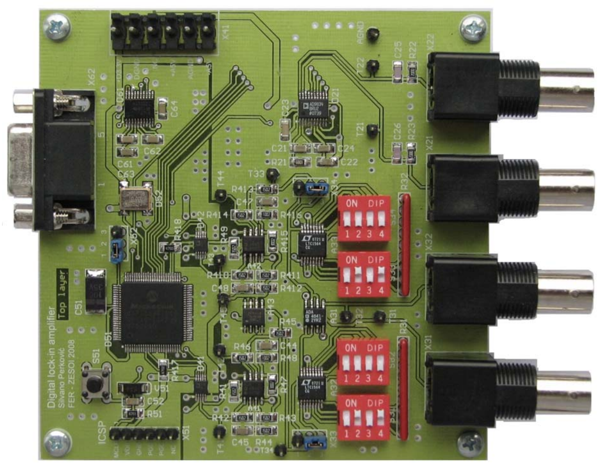

Fig. 3. Photograph of the digital module.

3.3. Measurement procedure

The measurement procedure consists of the following steps:

1. calibration of impedance measurement,
2. measurement of the coil impedance in the air, Z_{air}
3. measurement of the coil impedance in the tube, Z
4. calculation of the tube inner radius from the lookup table and tube contribution Z_T.

The gauge needs to be calibrated each time the test fixture (coil cables and connectors) is changed. We implemented open/short/load compensation using precision 100 Ω standard resistor.

Step 2, measurement of Z_{air}, is required in order to calculate impedance Z_T from the total coil impedance Z measured in step 3. Both measurements are corrected for coil stray capacitances. Step 2 is performed only when the coil is connected for the first time. Step 3 is repeated a number of times required to achieve stable readout independent on the coil radial offset as described in Section 2.3.

4. RESULTS

4.1. Comparison with HP 4284

For comparison, we measured the impedances of a set of resistors and coils using the presented electromagnetic gauge and RLC precision meter HP 4284 at the frequency 31250 Hz. Tables 1 and 2 contain an excerption of the results.

Discrepancy between the measurements made with the two instruments is less than 1‰ in magnitude and 0,01° in phase at the chosen frequency. The range of the nominal values in tables 1 and 2 (18–220 Ω and 0,5–1,4 mH) corresponds to the expected range of the impedance for the measurement coil from Section 4.2.

Table 1. Impedances of a set of resistors measured at 31250 Hz using the proposed gauge and RLC meter HP4284.

Nominal resistance R_{nom}, [Ω]	HP4284	Gauge	Discrepancy
	Measured imp. Z_1, [Ω]	Measured imp. Z_2, [Ω]	$p=\left\|\frac{Z_2-Z_1}{Z_1}\right\|$
18	18,12+0,01 j	18,12+0,00 j	0,6 ‰
22	21,97+0,01 j	21,97−0,01 j	0,9 ‰
47	47,58−0,01 j	47,56−0,02 j	0,5 ‰
75	75,45+0,02 j	75,41+0,00 j	0,6 ‰
100	99,76+0,02 j	99,71+0,01 j	0,5 ‰
120	119,86−0,01 j	119,80−0,01 j	0,5 ‰
150	149,55+0,01 j	149,46−0,04 j	0,7 ‰
180	179,09+0,00 j	179,00+0,01 j	0,5 ‰
200	200,29−0,02 j	200,20−0,05 j	0,5 ‰
220	220,32−0,01 j	220,21−0,01 j	0,5 ‰

Table 2. Impedances of a set of coils measured at 31250 Hz using the proposed gauge and RLC meter HP4284.

Coil (Nom. ind.) L_{nom}, [mH]	HP4284	Gauge	Discrepancy	
	Meas. imp. Z_1, [Ω]	Meas. imp. Z_2, [Ω]	$p=\left\|\frac{Z_2-Z_1}{Z_1}\right\|$	$\angle Z_2-\angle Z_1$ [10^{-3} °]
A (0,5)	4,32 +93,32 j	4,32 +93,22 j	1,0 ‰	−3
B (1,0)	6,36 +196,08 j	6,34 +195,99 j	0,5 ‰	5
C (1,0)	8,18 +210,80 j	8,15 +210,88 j	0,4 ‰	9
D (1,4)	7,95 +276,51 j	7,90 +276,37 j	0,5 ‰	10

4.2. Measurement of inner radius

We measured the inner radius of three tubes made of different materials using coil A (N_t=122, r_0=22,18 mm, L=40 mm), Table 2. The step between two consecutive values r_i and r_{i+1} in the lookup table is 0,1 mm. Tube properties as specified by manufacturers are given in Table 3, and the measurement results are given in Table 4. The results presented in the third column of Table 4 are taken from [10]. They are obtained for several mechanically centered coils and the same tubes as in Table 3 for the frequency range 1 kHz – 1MHz using HP4284 RLC meter and the inversion procedure based on the Nelder-Mead simplex algorithm. We provided these results as a reference for corroborating the gauge functionality and validity of its results (given in the fourth column of Table 4).

Although tubes 1 and 2 are made of the same material, their conductivities can differ for more than 10% of the nominal value (4,6 MS/m), whereas their reversible permeability at 31250 Hz can easily be anywhere between 10 and 200 depending on their magnetic history. The conductivity of annealed copper is around 58 MS/m. Thus, the proposed gauge is capable of measuring the inner radius for large variations of electromagnetic properties of both, ferromagnetic and nonmagnetic materials. The measurement accuracy remains unaffected as long as the excitation current (i.e. magnetic field) is low enough (<10 mA for the given coils) to allow linearization of the magnetic hysteresis curve as in the model of Section 2.1.

Table 3. Tube properties as specified by manufacturer.

Tube no.	Material	Magnetic	Nominal inner radius r_{nom} [mm]
1	steel (AISI 1035)	yes	25,4
2	steel (AISI 1035)	yes	35,1
3	copper (EN 1057)	no	25,5

Table 4. Measured inner radii of the tubes from the Table 3.

Tube no.	Nominal inner radius r_{nom} [mm]	Results from [10] r_{ref} [mm]	Measured using the proposed gauge r_{meas} [mm]
1	25,4	25,31±0,06	25,40±0,05
2	35,1	35,16±0,01	35,20±0,05
3	25,5	25,50±0,02	25,40±0,05

5. CONCLUSIONS

We adapted the coil-impedance method for measurement of the tube inner radius to a small scale embedded system suitable for field measurements. The measurement procedure is modified in order to match computational capabilities of a microcontroller. The result of the inversion procedure is tube inner radius corrected for variations of the tube electromagnetic properties and coil radial offset. The electromagnetic gauge can be used for both magnetic and nonmagnetic tubes and its performances are comparable to the laboratory implementation of the method based on the precision RLC meter. Our present work is focused on reducing the size and power consumption of the embedded system and further improvements in the inversion procedure.

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